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Wearable handwriting input device using magnetic field Geomagnetism cancellation in position calculation

Xinying Han*, Hiroaki Seki, Yoshitsugu Kamiya, Masatoshi Hikizu

Graduate School of Natural Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan

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A B S T R A C T

In this paper an efficient technique using magnetic field is proposed for wearable handwriting input. This device requires mounting a permanent magnet onto fingertip and detecting the magnetic field generated by the magnet through magnetic sensors at the wrist of the other hand. The position of magnet is calculated by the vector of the magnetic field. And a method is proposed to avoid geomagnetic influence, using two magnetic sensors. Numerical methods are used to calculate the position of magnet with geomagnetism cancellation. Two numerical methods have been adopted and compared. A prototype device is made and we succeeded to get the trajectory of handwriting input character.

1. Introduction

As information technology was developed quickly, many kinds of input devices were developed. They make our lives much more comfortable and convenient [1]. On the other hand, these devices have many disadvantages. For example, keyboard is too big to carry and requires training to get used to it. Mouse needs a plane to operate. Touch panel is good but requires a panel to work on, and its working space is limited within the panel [2]. Virtual keyboard needs a plane to put user's hands and has to be fixed somewhere [3]. Voice input has been developed greatly but it does not work well in noisy environment and needs much time to be used to it [4]. And for elder person, visually impaired and those who are not skilled in operation of computer, few devices are available. Further more, few devices are developed for the wearable computing [5].

Therefore we proposed a new device to fit the demand above. It is able to be used by almost everyone, including visually impaired, people who are not used to computer, and those working in noisy environment. This device does not need any plane or panel, just needs to be fixed onto user's hands. And user can be used to it without any training even user get it just now.

A basic device without geomagnetism cancellation has been proposed before [6] and here a new accurate device which is able to cancel the influence of geomagnetic field is proposed. Two numerical methods are adopted to cancel the geomagnetic field, and they have been compared in this paper.

2. Proposed handwriting input device

The device proposed (shown in Fig. 1) consists a permanent magnet which is mounted on fingertip, two magnetic sensors and their peripheral circuits attached on the wrist of other hand, an A/D converter which converts output voltage signal into digital one, and a PC to calculate the position of magnet.

In this device the permanent magnet is mounted on fingertip through a mounter like a ring while user writes characters on his palm. Two high sensitive multi-axis magnetic sensors are attached on the wrist of other hand, detecting the magnetic field generated by the permanent magnet continuously. Because the detected magnetic vectors generated by the magnet depend on the position of magnet, position of magnet is able to be calculated through the output of magnetic sensors. At the same time, geomagnetism cancellation will work while two sensors are working in difference mode. Finally, the trajectory of the magnet will be visualized as the trajectory of handwriting characters.

Here we would like to emphasize the cancellation of geomagnetism. In this device, trajectory of handwriting character is acquired by detecting the magnetic vector generated by the permanent magnet, which decreases proportional to third power of distance from magnet. But there is always an ambient magnetic field which influences magnetic sensor in actual environment. It contains geomagnetism mainly and brings great error when

* Corresponding author. Tel.: +81 76 234 4705; fax: +81 76 234 4706.
E-mail addresses: hanxinying@hotmail.com (X. Han), hseki@t.kanazawa-u.ac.jp (H. Seki).

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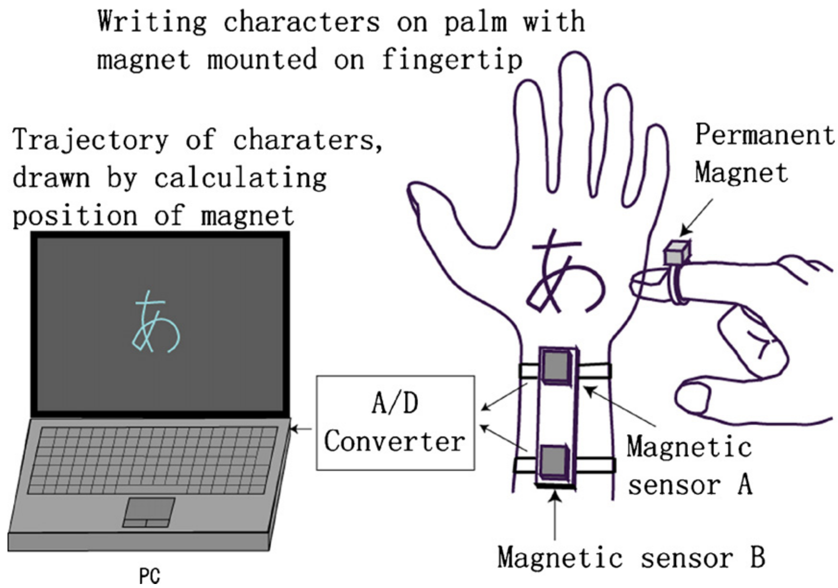

Fig. 1. Image of handwriting input device.

magnet is far away from magnetic sensor. So geomagnetism cancellation is important to get the position of magnet correctly. In order to get rid of this influence of geomagnetism, two magnetic sensors which are set separately in the same plane are adopted, working in difference mode. One of the sensors is set near palm and the other one is set far. Because geomagnetic field is almost same at two positions, geomagnetic field can be cancelled when the difference of two magnetic sensors is taken.

This device has following characters and advantages:

- This device does not require any character patterns. User just needs to write down the characters on his palm. So not only characters, but also numeral, drawing can be input.
- Character recognition method is needed to recognize handwritten characters form trajectories.
- This device is compact and easy to carry out. It will not disturb user's motion and is able to be worn outside. It just needs to put a mounter onto fingertip. So it can be used as wearable inputting device.
- There is no writing pad or frame in this device.
- This device is liable in lots of environments. Because magnetic field will not be disturbed by body, cloth and so on, it can work in almost everywhere, even on the bed.
- No training or practice is necessary. User just needs to write down what he wants to input on his palm.

3. Calculation of magnet position

After magnetic vector generated by the magnet is detected by magnetic sensors, position of magnet is necessary to be calculated, following the theory of magnetism. The relationship between magnetic vector and position of magnet is expressed in the following sections.

3.1. Magnetic vector generated by magnet

The relationship between magnetic vector and magnet is shown in Fig. 2. It is assumed that magnet exists in the same plane which magnetic sensor is in. It is also assumed that the magnetic axis of magnet (axis of S and N) is in parallel with the axis of magnetic sensor (axis of x) and the parallel relationship does not change during inputting. In calculation, magnet is assumed as a magnetic dipole [7], and magnetic sensor is assumed as a point.

Magnetic vector H generated by magnet at magnetic sensor can be decomposed into two components, H_r in the direction from magnetic sensor to magnet, and H_θ in the direction which is perpendicular to H_r. H_r and H_θ are given by

$$H_r = \frac{2K\cos\theta}{r^3}, \quad H_\theta = \frac{K\sin\theta}{r^3}, \quad K = \frac{m}{4\pi\mu} \tag{1}$$

$$r = \sqrt{x^2 + y^2}, \quad \cos\theta = -\frac{x}{r}, \quad \sin\theta = \frac{y}{r} \tag{2}$$

Here μ is the magnetic permeability, m is the magnetic moment, θ is the angle between the N axis of magnet and the sensor direction from the magnet origin, and (x, y) is the position of magnet in the magnetic sensor oriented coordinate. The magnetic vector H can be also decomposed into H_x and H_y (components of x-axis and y-axis), distributing H_r, H_θ to x and y directions.

$$H_x = H_r\cos\theta - H_\theta\sin\theta = \frac{K}{r^3}(3\cos^2\theta - 1) = K\frac{2x^2 - y^2}{(x^2 + y^2)^{5/2}} \tag{3}$$

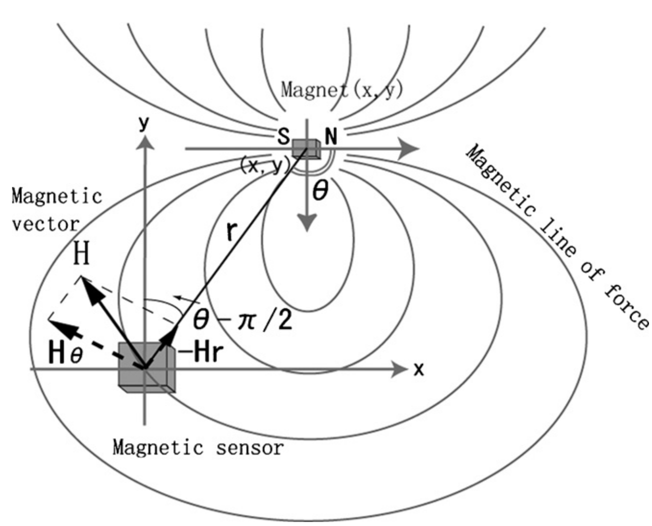

Fig. 2. Magnetic vector generated by magnet.

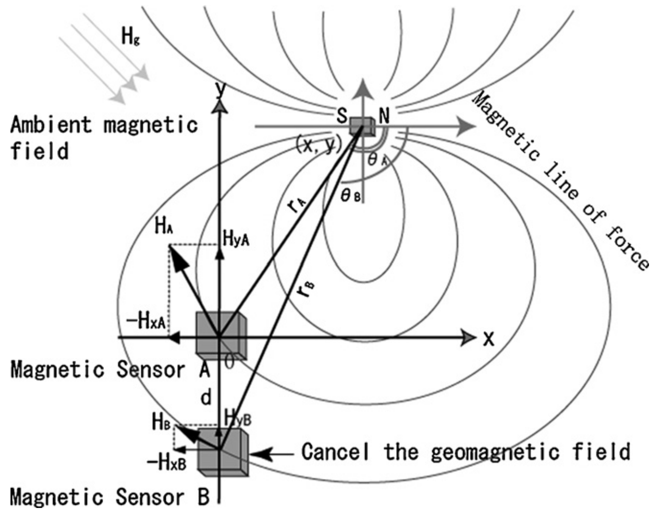

Fig. 3. Relationship between two sensors and magnet.

$$H_y = -H_r \sin\theta - H_\theta \cos\theta = -3K\frac{\cos\theta \sin\theta}{r^3} = 3K\frac{xy}{(x^2+y^2)^{5/2}} \quad (4)$$

3.2. Calculation of position of magnet without geomagnetism cancellation

In case geomagnetic field is ignored, position of magnet (x, y) can be obtained from Eqs. (3) and (4), when magnetic vector H (H_x, H_y) is known. Removes r and K from Eqs. (3) and (4), the following equation can be obtained:

$$H_y(3\cos^2\theta - 1) = H_x(-3\cos\theta\sin\theta) \quad (5)$$

Both the neighborhoods of Eq. (5) are squared, the secondary equation about $\cos^2\theta$ is obtained by use of the relation of $\sin^2\theta$=$1 - \cos^2\theta$. By solving the secondary equation about $\cos^2\theta$,

$$P = \cos^2\theta = \frac{(3H_x^2 + 2H_y^2) + H_x\sqrt{9H_x^2 + 8H_y^2}}{6(H_x^2 + H_y^2)}, \cos\theta = \pm\sqrt{P} \quad (6)$$

Then we use the next relationship from Eqs. (3) and (4).

$$\begin{aligned} H_x^2 + H_y^2 &= \frac{K^2}{r^6}[(3\cos^2\theta - 1)^2 + (-3\cos\theta\sin\theta)^2] \\ &= \frac{K^2}{r^6}[(3P-1)^2 + 9P(1-P)] \end{aligned} \quad (7)$$

So r can be gotten by

$$r = \sqrt[6]{K^2\frac{3P+1}{H_x^2 + H_y^2}} \quad (8)$$

The angle θ should be taken in the range $[0,\pi]$ because magnet is always set upon x-axis. So + should be selected for $\cos\theta$ in case of $H_y \le 0$, and − should be selected for $\cos\theta$ in case of $H_y \ge 0$. The position of the magnet (x, y) can be gotten by following equations:

$$x = r\cos\theta, \quad y = r\sin\theta = r\sqrt{1-P} \quad (9)$$

3.3. Calculation of position of magnet with geomagnetism cancellation

In order to get rid of the influence of geomagnetic field, two magnetic sensors working in difference mode are adopted. Relationship between two magnetic sensors and magnet is shown in Fig. 3.

Here the distance between sensor A and sensor B is d. Magnet locates in position (x, y) in the magnetic sensor A oriented coordinate. The angle between N axis of magnet and sensor A direction from magnet origin is θ_A. The angle between N axis of magnet and sensor B direction is θ_B.

Since the device works in the environment which a almost stable geomagnetic field H_g exists, composite magnetic vectors generated by magnet and geomagnetic field at sensor A and sensor B are detected as H_A and H_B, which contain same component H_g. They can be decomposed into two components in the directions of x, y-axis, which are expressed as H_{xA}, H_{yA}, H_{xB}, H_{xB}. From Eqs. (3) and (4) H_{xA}, H_{yA}, H_{xB}, H_{xB} can be given by following equations:

$$H_{xA} = K\frac{2x_A^2 - y_A^2}{(x_A^2 + y_A^2)^{5/2}} + H_{gx} \quad (10)$$

$$H_{yA} = 3K\frac{x_A y_A}{(x_A^2 + y_A^2)^{5/2}} + H_{gy} \quad (11)$$

$$H_{xB} = K\frac{2x_B^2 - y_B^2}{(x_B^2 + y_B^2)^{5/2}} + H_{gx} \quad (12)$$

$$H_{yB} = 3K\frac{x_B y_B}{(x_B^2 + y_B^2)^{5/2}} + H_{gy} \quad (13)$$

Here H_{gx}, H_{gy} are the decomposed components of ambient magnetic field H_g in x, y directions. (x_A, y_A) is position of the magnet in the coordinate where sensor A is origin. (x_B, y_B) is position of the magnet in the coordinate where sensor B is origin. The relationship between x_A, y_A, x_B, y_B, x and y is shown by following equation:

$$x = x_A = x_B, \quad y = y_A = y_B - d \quad (14)$$

From Eqs. (10)–(14) the relationship between the difference of magnetic fields at two sensors and position of magnet (x, y) can be yielded by following equations:

$$f_x(x,y) = H_{xB} - H_{xA} = K\left\{\frac{2x^2 - (y+d)^2}{[x^2 + (y+d)^2]^{5/2}} - \frac{2x^2 - y^2}{(x^2+y^2)^{5/2}}\right\} \quad (15)$$

$$f_y(x,y) = H_{yB} - H_{yA} = 3K\left\{\frac{x(y+d)}{[x^2 + (y+d)^2]^{5/2}} - \frac{xy}{(x^2+y^2)^{5/2}}\right\} \quad (16)$$

Here $H_{xB} - H_{xA}$ and $H_{yB} - H_{yA}$ are the differences of outputs of magnetic sensors.

4. Numerical methods in position calculation

Despite position of magnet can be calculated by Eqs. (15) and (16), actually it is difficult to be solved directly. Numerical methods, including steepest descent method (SD-method) [8] and Newton–Raphson method (NR-method) [9], are adopted to solve the problem above.

4.1. Steepest descent method

SD-method is a popular iterative method for solving large system of equations. It is effective for the systems like Eqs. (15) and (16). In SD-method calculation starts at an arbitrary point (x_0, y_0) and slides down to the bottom of the paraboloid. When we take a step, we choose the direction in which target function decreases most quickly, which is the opposite direction of (f_x', f_y'). And we assume that the target function is

$$F(x,y) = f_x^2(x,y) + f_y^2(x,y) \quad (17)$$

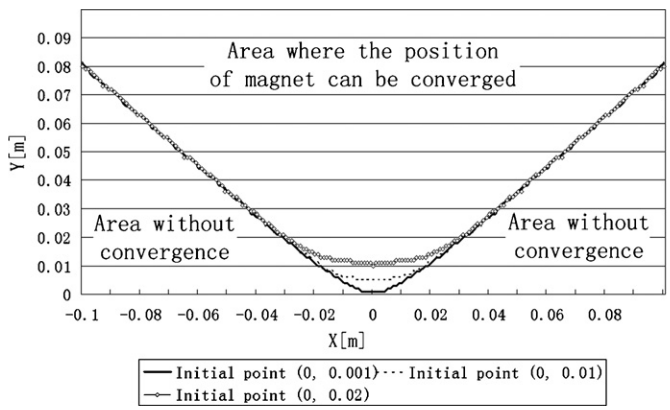

Fig. 4. Comparison of different initial points in SD-method.

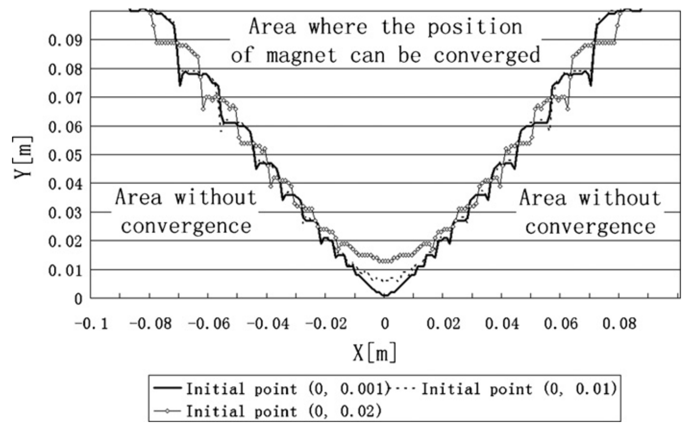

Fig. 5. Comparison of different initial points in Newton–Raphson method.

The $k+1$ ($k=0, 1, 2,\ldots,n$) step can be yielded by following equations:

$$\begin{bmatrix} x_{k+1} \\ y_{k+1} \end{bmatrix} = \begin{bmatrix} x_k \\ y_k \end{bmatrix} - \frac{F(x_k, y_k)}{F_x^2(x_k, y_k) + F_y^2(x_k, y_k)} \begin{bmatrix} F_x(x_k, y_k) \\ F_y(x_k, y_k) \end{bmatrix} \tag{18}$$

Here F_x, F_y are the partial differential of target function $F(x, y)$. Calculation will take a series of steps until (x_k, y_k) is close enough to the solution (x, y). The calculation should be continued until the target function $F(x, y) < \varepsilon$, where ε is the accuracy control parameter.

Because local minimum of target function exits, a proper initial point has to be found out to get the maximal calculable area. In order to get a symmetrical calculable area, we select the points over y-axis. Different initial points have been compared by simulation as shown in Fig. 4.

The distance between two magnetic sensors in the simulation is 20 mm. The area over the lines is calculable, and the area under the lines is incalculable. From simulation we can know that the larger calculable area can be gotten when the initial point is closer to the origin point. So point (0, 0.001) is selected to be the initial point.

4.2. Newton–Raphson method

NR-method is other effective method to solve the system like Eqs. (15) and (16). In NR-method calculation starts at an arbitrary point (x_0, y_0). The $k+1$ ($k=0, 1, 2,\ldots,n$) step is given by the following equation:

$$\begin{bmatrix} x_{k+1} \\ y_{k+1} \end{bmatrix} = \begin{bmatrix} x_k \\ y_k \end{bmatrix} - J^{-1} \begin{bmatrix} f_x(x_k, y_k) \\ f_y(x_k, y_k) \end{bmatrix} \tag{19}$$

Here $J(x_k, y_k)$ is the Jacobi-Matrix of Eqs. (15) and (16). It is governed by

$$J(x_k, y_k) = \begin{bmatrix} f_{xx}(x_k, y_k) & f_{xy}(x_k, y_k) \\ f_{yx}(x_k, y_k) & f_{yy}(x_k, y_k) \end{bmatrix} \tag{20}$$

$f_{xx}(x_k, y_k), f_{xy}(x_k, y_k), f_{yx}(x_k, y_k), f_{yy}(x_k, y_k)$ are the partial differentials of $f_x(x, y)$ and $f_y(x, y)$. Calculation should be iterated until $\max(f_x(x, y), f_y(x, y)) < \varepsilon$, where ε is the accuracy control parameter.

Since not all points are calculable because of data overflow and local minimum which depends on the initial point, numerical simulation has been done to find out the best initial point. From the simulation it is known that initial point should be on y-axis to get a symmetrical calculable area. We compared different initial points on y-axis as shown in Fig. 5.

In the simulation distance between two magnetic sensors is 20 mm. The area over the lines is calculable, and the area under the lines is incalculable. From simulation, we can know that the closer initial point to x-axis, the larger calculable area comes. Finally we choose the initial point (0, 0.001).

4.3. Comparison of SD-method and NR-method

Because local minimum of function and data overflow exist, not all the points can be calculated by either SD-method or NR-method. We can know that SD-method leads to a larger calculable area than NR-method from Figs. 4 and 5.

On the other hand, the average error, average iteration times and amount of calculable points of NR-method are less than those of SD-method, as shown in Table 1. In the simulation we have calculated 40200 points in the rectangle with the corner of (−0.1, 0.001) and (0.1, 0.2) (m). Although NR-method is much more accurate and effective than SD-method, we still choose SD-method because it can bring us a larger calculable area, which is the most important issue in this device.

5. Prototype device

A sample device has been made on trial. A permanent magnet is mounted on the fingertip by a mounter like a ring. It is neodymium type, and its size is 6 mm × 6 mm × 4.5 mm. During use the axis of magnet has to be kept to be parallel with the x-axis of magnetic sensors. Two 2-axis magnetoresistive sensor ICs (Honeywell® HMC1022; range: ±6 gauss; sensitivity: 1.0 mV/(V gauss); resolution: 85 μgauss; bandwidth: 5 MHz) are adopted as magnetic sensors to detect the magnetic field continuously. In the magnetic sensor there are two field offset straps (x- and y-axis) to generate opposite magnetic fields to compensate the applied magnetic fields, making the sensor more sensitive. Therefore a closed loop current feedback circuit is adopted to get accurate result. Output of magnetic sensor will be fed back to the offset strap through differential amplifiers. The magnetic sensor detects the magnetic field and then induces an output voltage signal. In order to cancel the influence of geomagnetic field, one more magnetic sensor B is put at the position which is 50 mm away from sensor A on its y-axis. The outputs of two magnetic sensors are input to PC via an A/D converter. The electric circuit of the device is shown in Fig. 6, and the prototype device is shown in Fig. 7.

The differences of outputs of each axis are taken and calculated as $H_{xB} - H_{xA}$ and $H_{yB} - H_{yA}$ to get the position of magnet by solving Eqs. (15) and (16) with SD-method. The trajectory of magnet is

Table 1
Comparison of SD-method and NR-method

	Avg. error (m)	Avg. iteration times	Calculable points
SD-method	1.2e−5	46.4	32756/40200
NR-method	7.1e−8	22.3	27986/40200

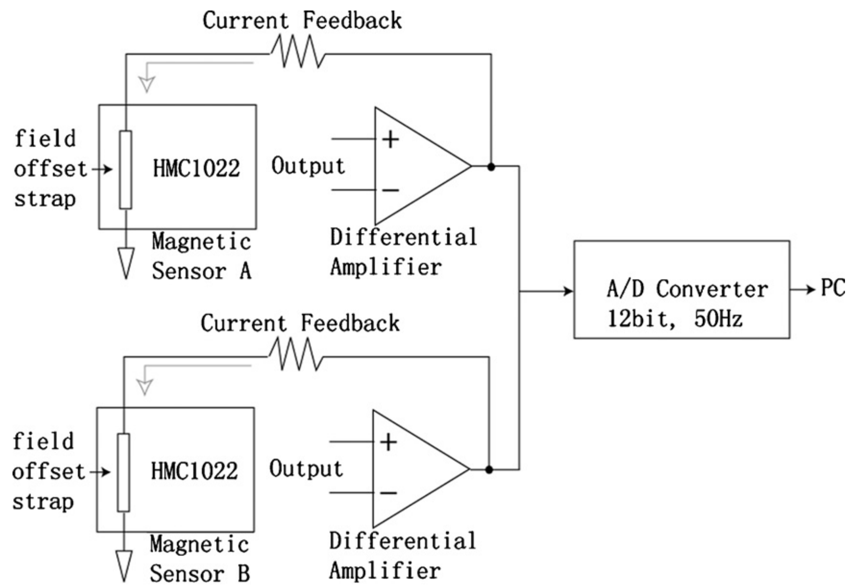

Fig. 6. Electric circuit for detecting magnetic field.

visualized by an OpenGL program as the trajectory of the inputted characters.

6. Experimental results

6.1. Relationship between output of sensors and position of magnet

In the equations for calculating position, coefficient K is unknown because it depends on magnet, sensor, circuit and so on. So before experiments the relationship between the output of device and position of magnet has to be investigated at first. From Eqs. (3) and (4) it is known that y direction output of device will be zero when magnet moves along y-axis. Coefficient K can be gotten through following equations:

$$H_x = -\frac{K}{y^3}, H_y = 0 \tag{21}$$

Here H_x, H_y will be expressed as the values of output voltages, which are proportional to the magnetic vector generated by magnet. Since position of magnet is known, coefficient K can be solved by curve fitting as shown in Fig. 8. From experiment we got that coefficient K should be 0.00031.

6.2. Result of geomagnetism cancellation

After coefficient K is gotten, experiment is done to confirm that geomagnetism cancellation works well or not. Magnet is set to 30 points in the rectangle with the corner of (−0.04, 0.05) and (0.04, 0.15) (m). The distance between two sensors is 50 mm. Position of the magnet is calculated from the differences of two magnetic sensors by Eqs. (6), (8) and (9) (calculation without geomagnetism cancellation), and the result is shown in Fig. 9; Fig.10 shows how it will be when the position is calculated by Eqs. (15) and (16) with geomagnetism calculation.

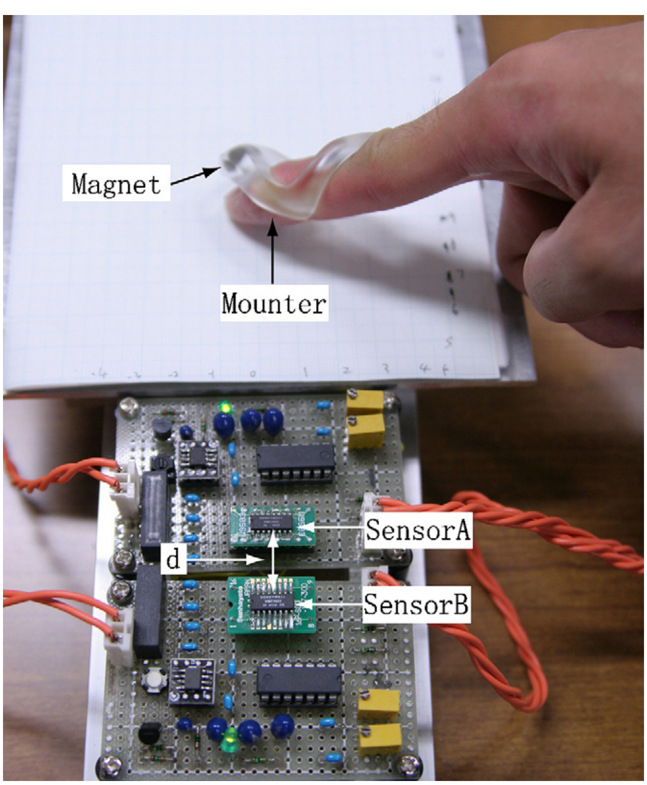

Fig. 7. Prototype device.

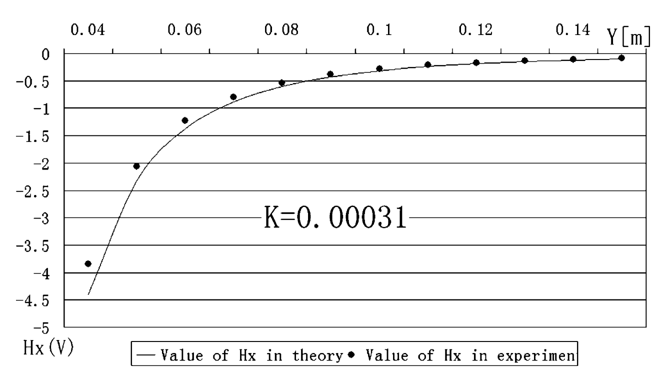

Fig. 8. Curve fitting in calculation of K.

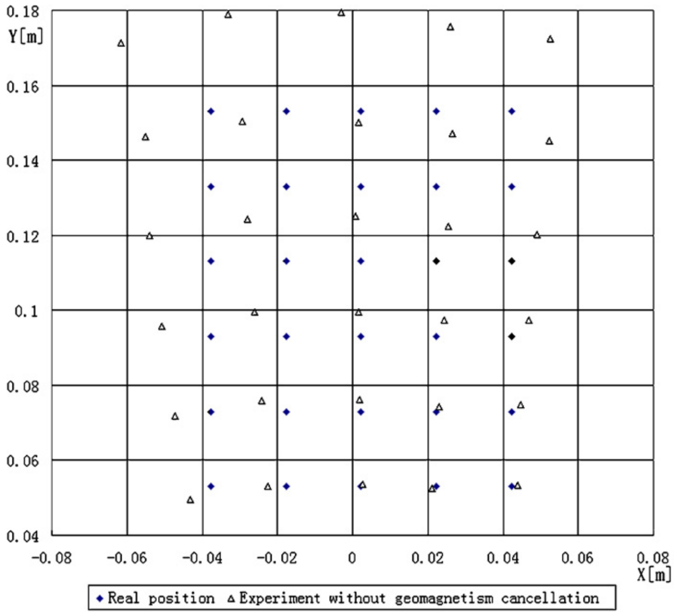

Fig. 9. Result of experiment without geomagnetism cancellation.

From Fig. 9 we can know that, without geomagnetism cancellation magnet is calculated to the position which is far away from its real position. The maximum error of position of magnet is about 30 mm at the upper corner of the rectangle.

When geomagnetism cancellation works, accurate position can be gotten. In the experiment, the maximum error of position of magnet is about 10 mm at the upper corner of the rectangle, which is evidently smaller. It will not confuse us in handwriting input at all.

In the experiment, all the points depart from their real positions. The possible reasons are shown as below:

- It is difficult to place the small magnet paralleled to the magnetic sensors precisely.
- The coordinates of two sensors are not parallel perfectly too.

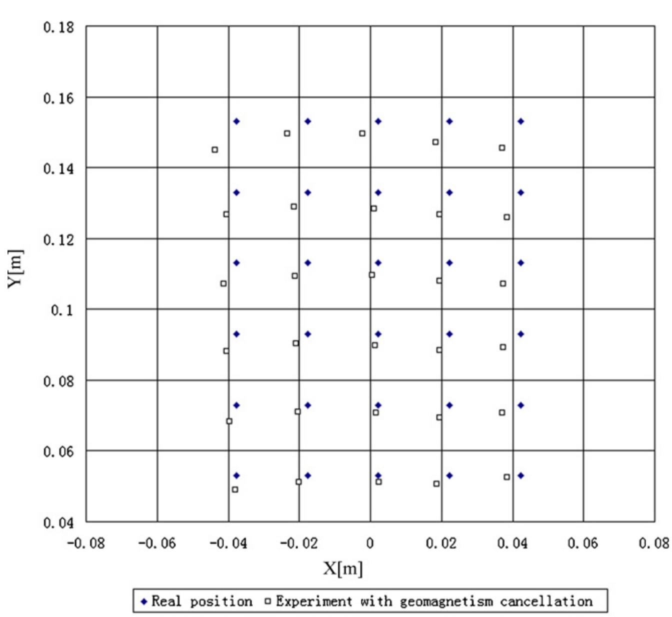

Fig. 10. Result of experiment with geomagnetism cancellation.

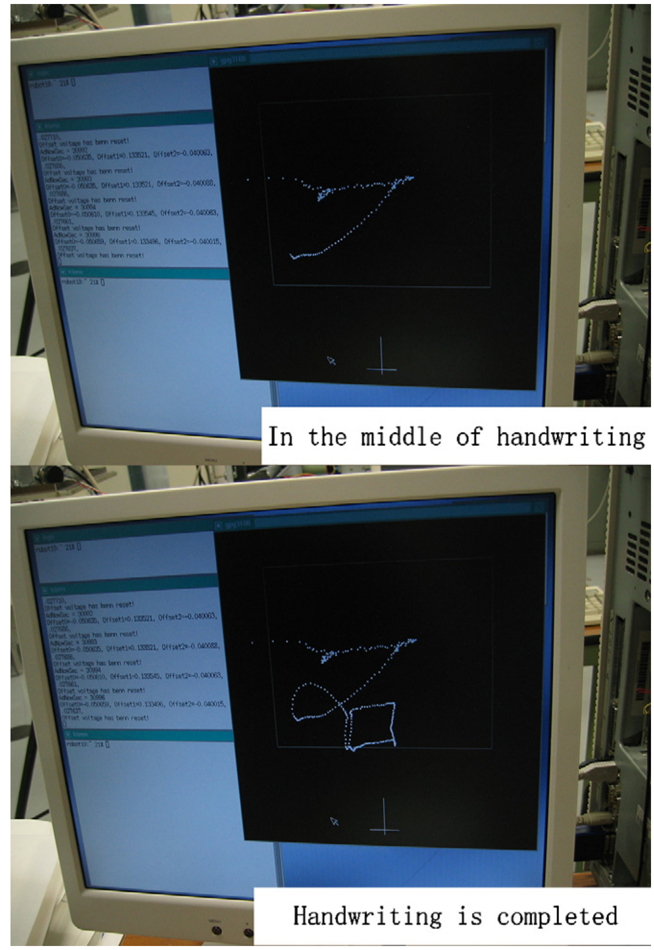

Fig. 11. Example of inputting handwriting character (kanji "stone").

- We used curve fitting to get the value of coefficient K. It brings us error.
- There are noise and nonlinearity in the circuit and magnetic sensor IC.

6.3. Input of handwriting characters

We used the prototype handwriting input device to obtain the trajectories of handwritten characters on PC. An example is shown in Fig. 11. Here sampling frequency of detecting the position of magnet is 50 Hz, and geomagnetism cancellation is working. Though some distortions are seen, a continuous trajectory of handwritten character can be acquired. Unlike normal handwriting input devices, all the movements, including those between strokes of characters, are obtained without distinction. When the magnet is moved outside the rectangle with the corner of (−0.04, 0.05) and (0.04, 0.15) (m), character which has been written will be erased. And a new character can be input.

Since characters are inputted by the trajectory of magnet, all kinds of characters (for example, kanji, alphabet, numeral and so on) can be inputted theoretically if character recognition software supports.

7. Conclusion

A novel handwriting input device which uses magnetic field has been proposed. A prototype device was made and succeeded to get the correct position of magnet with geomagnetism cancellation, using the steepest descent method. This device can work with small error. It is useful to input many kinds of characters, depending on the character recognition software. This device can be used as not only a handwriting device but also a new user interface of wearable computing.

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